STUDY OF GAMMA-ALPHA PHASE TRANSFORMATION IN 18-8 STAINLESS STEEL BY COLD WORK

by

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INTRODUCTION

There are two groups of the chromium-nickel alloys classed as austenitic stainless steels. One group, in which austenite is stable at room temperature, contains nickel more than necessary to balance chromium for getting stable austenite at room temperature. This group may also contain Ti or Columbium in small amounts to stabilize the austenite. Another group, in which austenite is metastable at room temperature, contains nickel just sufficient to get austenite at room temperature. By application of cold work this metastable austenite tends to reach equilibrium state by forming body centered cubic ferrite (alpha-phase). Because the ferrite thus formed contains carbon in supersaturated solution, it is sometimes called as "Pseudo-Martensite" or "Martensite."

One of the most important of the metastable alloys, contains 18 percent chromium and 8 percent nickel and is generally known as 18-8 chromium-nickel steel. Generally in this type of alloy chromium content ranges between 17 and 20 percent and nickel content ranges between 7 and 10 percent with small quantities of other alloying elements such as manganese, molybdenum and silicon. The carbon content ranges from 0.01 to 0.2 percent.

Changes in mechanical and chemical properties of 18-8 stainless steel subjected to cold work has long been the subject of extensive study. Much of the interest centers around the ability of this steel to transform from face centered cubic austenite (gamma-iron) which is nonmagnetic to body centered cubic ferro-magnetic (alpha-iron).

The gamma to alpha phase transformation in 18-8 stainless steels have been studied in the past to some extent by means of magnetic testing,

electrical conductivity observations and microscopic observations along with X-Ray diffraction technics.

History

The gamma-alpha phase transformation was first reported by E. Maurer (9) in 1909 when he observed a change in the structure and magnetic properties occurred by cold working in austenitic maganese steel. After that F. Wever (14) in 1921 showed by X-Ray diffraction methods that a transformation from gamma to alpha phase has been induced by cold working.

Aborn and Bain (1) observed this phase transformation in 1930, while studying the nature of nickel-chromium rustless steels. They studied the extent of phase transformation by both X-Ray diffraction methods and magnetic permeability measurements. In the same year, Pilling (11) while studying the effect of nickel content in austenitic stainless steels observed this phase transformation while cold working by rolling and noting changes in magnetic permeability. In 1937, Krivobok and Lincoln (7) studied properties and characteristics of austenitic stainless alloys. They too adopted cold rolling for cold working and observed increase in tensile strength and magnetic permeability as a result of ferrite formation. Austin and Miller in 1940 (3) studied the influence of heat treatment and cold work on the magnetic permeability of some austenitic iron-chromium-nickel alloys. For cold work they employed rolling for strip and drawing for wire of 18-8 stainless steel. They related the increase in permeability with percentage reduction by cold work of the sample. In 1942, Mathieu (8) contributed important information regarding the effect of the alloy content and the conditions of cold working upon the gamma-alpha transformation of austenitic

steels. He considered three different types of deformation, pulling through a die (drawing), rolling and stretching. He found clearest results with the stretching experiments and relating them with increased magnetic permeability.

Post and Eberley (12) studied the stability of austenite in stainless steels in 1946. They also used cold rolling as a method of cold deformation and related the data with increased magnetic permeability. Binder (4) in 1950 observed by magnetic test that a 18-8 valve stem after 15 years of use in equipment making liquid oxygen had transformed partially to martensite under the influence of service strains at low temperature (near -300° F).

In 1953, Angel (2) and later on Cina (5) studied the effect of cold work on gamma-alpha transformation in austenitic stainless steels. Cina noted that transformation could be induced more easily (1) by compression at temperatures below 70° F and (2) by tension rather than compression at room temperature. In 1955 Fiedler, Averbach and Cohen (6) studied the effect of deformation on the martensitic transformation in austenitic stainless steels. They used swagging as the methods of deformation and for estimating phase transformation they used change in electrical resistance of the samples since the electrical resistance increases with increasing phase transformation.

In 1957, Powell, Marshall and Backofen (13) studied strain hardening characteristics of austenitic stainless steel as functions of temperature, strain rate and stress system and correlated them with the progress of the martensitic transformation. They determined quantitatively relationships between extent of transformation and plastic strain through measurements of the density of the deformed samples.

Considerable work has been reported on the extent of cold work in terms of change in cross section related to phase transformation. None of

the above works however give any definite relation between the amount of input work and the corresponding degree of phase transformation.

Purpose

Plastic deformation can be accomplished by several ways such as rolling, stretching, drawing, torsion, etc. In this research torsion was used as the method of cold working. The purpose of this investigation was to find quantitatively a relation between the work input and the amount of phase transformation from gamma to alpha which occurs as a result of cold work. Changes in ferro-magnetic characteristic of the samples were used for determining the amount of phase transformation, since gamma iron is nonmagnetic and alpha iron is magnetic.

The investigation was carried out under two different sets of temperature conditions. Under the first set, the cold work by torsion was done at room temperature while under the second set, the cold work was done at subzero temperature by covering the sample in dry ice (solid carbon dioxide).

REVIEW OF LITERATURE

A survey of literature revealed general agreement among the various authors regarding the phase transformation induced by cold work in 18-8 stainless steels.

As early as in 1930, R. H. Aborn and E. C. Bain (1) examined austenitic chromium-nickel alloys to determine their stability towards phase transformation. Theyobserved that the "18-8 alloy itself is truly stable only as ferrite at temperatures below about 400° C (750° F) but

indefinite maintenance at this temperature will not in itself cause the alloy, as quenched in the austenitic conditions, to transform from metastable austenite to stable ferrite. Cold work, however supplies the necessary atomic "stirring" to induce the alloy, at least partially, to assume its stable condition.

Pilling (11) reported in the same year that the groups of compositions commonly described as austenitic should properly be split up into two groups, a "marginal austenitic" group and a "stable austenitic" group. The latter has qualities of permanence which the marginal alloys do not have. The 18 percent chromium, 8 percent nickel composition lies within the range of marginal alloys ..... the alloy 18 percent chromium and 8 percent nickel was wholly austenitic only when quenched from 800° C or above; it precipitated alpha iron when heated to 700° C or when strained following quenching from any of these temperatures.

He also suggested that the marginal range can only be escaped by increasing either nickel or chromium content; it is accomplished most effectively by an increase in nickel. An increase to 12 percent Ni is sufficient to secure stability in the austenitic form.

Further works of Krivobok and Lincoln (7), Austin and Miller (3) and Post and Eberley (12) gave deep insight of this phenomenon.

Austin and Miller (3) studied magnetic aspects of this phase transformation extensively. On the basis of their experiments they observed that "austenitic iron-chromium-nickel alloys, if free from ferrite, all have practically the same permeability, i.e., 1.003 (permeability of air being unity)... The 18-8 group become ferromagnetic if sufficiently cold worked."

Further they suggested that in all cases where minimum permeability is an important factor in an alloy of the 18-8 type, the nickel chromium ratio should be kept as high as possible. Also care should be used in handling 18-8 material which has been treated to obtain a very low permeability since rough treatment such as hammering or bending may cold work the material locally enough to produce spots of ferrite. Thus a piece of 18-8 which is acceptable when tested may, if abused in handling, become unacceptable by the time it is put in service.

Post and Eberly (12) derived a formula to study the stability of chromium-nickel austenite,

$$\% \, Ni_{theoretical} = \frac{(\% \, Cr + 1.5 \times \% \, Mo - 20)^2}{12} - \frac{Mn}{2} - 35 \times \% \, C + 15.$$

$\% \, Ni_{theoretical}$ is defined as the nickel content which will just make the alloy completely stable as austenite. From this, a new parameter $\triangle$ is evolved which expresses quantitatively the instability or stability of an austenitic according to its composition.

$$\triangle = \% Ni_{analytical} - \% \, Ni_{theoretical}$$

where $\% \, Ni_{analytical}$ is the analytical percent nickel in the alloy, and $\% \, Ni_{theoretical}$ is the theoretical percent nickel which will just make the austenite completely stable on the basis of above formulae. Then for positive values of $\triangle$, the alloy will have more nickel than is necessary to make it completely stable, whereas for negative values of $\triangle$, the nickel is not sufficient to make the alloy austenite completely stable.

Further, the more negative the value of $\triangle$, the greater the instability and the less cold work which will be necessary to cause the appearance of pseudo-martensite. Similarly the more positive the value of $\triangle$, the further the analysis lies in the austenitic field away from the boundary between the gamma and gamma + martensite regions.

Binder (4) observed that an 18-8 valve stem, after 15 years of use in equipment making liquid oxygen, transformed partially to martensite under the influence of service strains at low temperature (near -300° F). A rough magnetic test showed no evidence of transformation except where it had been subject to strain.

Cina (5) has found that the nature of applied stress can also exert considerable influence on the extent of martensite formation during plastic deformation. In a comparison of tensile and compressive deformation, he found that for a given strain, tensile extension produces the greater amount of martensite.

Mathieu (8) has shown that strain rate can have a marked influence on the martensitic transformation. Specifically less transformation has been observed to accompany higher strain rate, an effect attributed to the temperature rise in increasingly rapid rate of deformation.

Fiedler, Averbach and Cohen (6) noticed that the amount of martensite produced by plastic tensile strain is increased as the temperature of deformation is lowered and as the amount of deformation is increased.

From the broad coverage of previous research, there seems to be common agreement that temperature, type of stress, steel analysis, plastic strain and strain rate have an influence on the gamma to alpha transformation.

THEORY OF GAMMA-ALPHA PHASE TRANSFORMATION BY COLD WORK

To understand the austenitic stainless steel, it is necessary to consider the ternary iron-chromium-nickel diagram. Since the standard stainless steel called 18-8 contains about 18 percent Cr and 8 percent Ni, it is possible to understand the essential role of nickel by considering a vertical section at 18 percent chromium through the ternary diagram. Similarly to understand the role of chromium a vertical section at 8 percent nickel through the ternary diagram should be studied.

These diagrams are shown in Figure 1 and are developed by Aborn and Bain (1). Nickel as well as chromium are both soluble in alpha and gamma iron. When in solution, nickel lowers A_3 point where alpha iron transforms to gamma iron on heating, and where gamma iron transforms to alpha iron on cooling and makes these allotropic changes, especially the one on cooling, very slowly. Chromium restricts the temperature concentration region where gamma solid solution is stable, that is, it produces a gamma loop. Nickel, on the contrary, increases the limit of this area.

When 18-8 stainless steel is heated a phase change occurs at about 660° F and some of the alpha solid solution changes to gamma solid solution. If the alloy is heated still further this allotropic change continues until at 1200° F all the alpha has changed to gamma. There is no further change if the heating is continued almost to the melting point. Now, if the alloy is cooled, the reversed change should take place, that is, gamma should be completely transformed at 660° F. Because of the sluggishness of the action, however, only small amount of alpha is actually formed on slow cooling and it is relatively easy to suppress by rapid cooling the formation of any

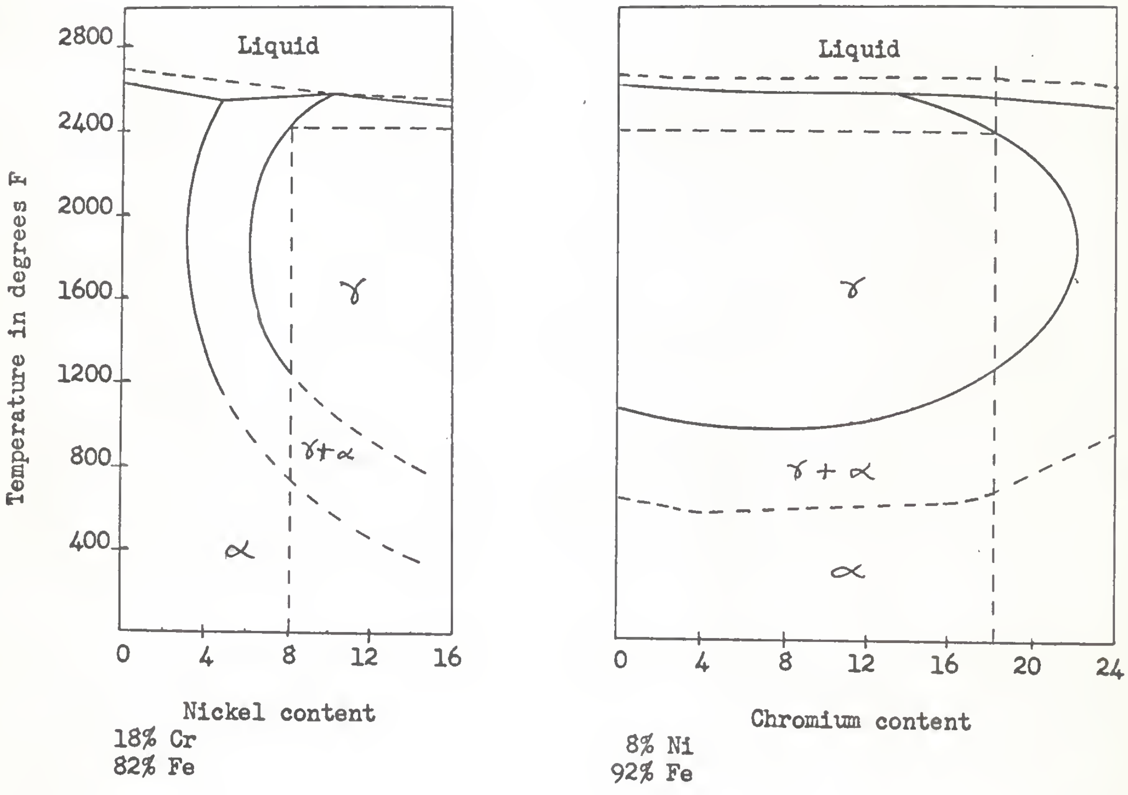


Fig. 1. Effect of addition of nickel (left) and of chromium (right) on the constitution of the 18% Cr, 8% Ni alloy.

alpha phase and thus to obtain an alloy that is entirely austenitic at room temperature.

Thus the 18-8 stainless steel is not in equilibrium condition which would be largely ferritic at ordinary temperature but it is prevented from changing to ferrite by substantially zero rate of spontaneous transformation at these temperatures.

Cold work acts as an accelerator and tends to produce magnetic chromium-nickel ferrite, known as pseudo-martensite or martensite. The magnitude of the effect accompanying a given amount of cold work depends largely upon the ratio of concentration of chromium to that of Ni and carbon, because both nickel and carbon tend to stabilize austenite. For a given chromium content an 18-8 alloy which is high in nickel or carbon or both is transformed to a lesser degree by a given amount of cold work, than a similar alloy low in carbon or in nickel or both.

The M_s temperature (the temperature at which martensite transformation starts) is lowered considerably by addition of various alloying elements. Several empirical equations are available from which M_s can be estimated to better than 50° F. One of such equation derived by Nehrenberg (10) is

$$M_s\ (^\circ F) = 930 - 540 \times \%\ C - 60 \times \%\ Mn - 40 \times \%\ Cr - 30 \times \%\ Ni - 20 \times \%\ Si$$

Where alloy contents are expressed in weight percent.

For 18 % Cr - 8% Ni stainless steel M_s goes below room temperature and hence in this type of steel the transformation is arrested at room temperature.

Although externally applied deformational energy may be rather small when averaged over the entire volume of the specimen, this energy really concentrates first at the strain centers and supplies a considerable part of the activation energy for the shear transformation. Consequently, plastic deformation stimulates martensite formation even above M_s. However, the amount of martensite produced by a given degree of deformation decreases with increasing temperature.

The austenite (gamma iron) of 18-8 stainless steel is soft and ductile. By cold working it transforms partly into pseudo-martensite and untransformed austenite. The strengthening of this austenite by cold work is due to the pseudo-martensite (alpha iron) and strain hardening of untransformed austenite and strain hardening of the transformed product, namely pseudo-martensite. Due to this strain hardening tensile strength and hardness increases with the resulting decrease in ductility.

As increase in hardness of cold worked 18-8 stainless steel is due to the strain hardening effect of cold work and also change in magnetic properties of this cold worked steel is due to the phase transformation induced by cold work, they can be correlated. Some authors have related the increased tensile strength with increasing magnetic permeability while some of them have related increase in hardness with increase in magnetic permeability in their works.

APPARATUS

To carry out the phase transformation by cold work and to measure the work input, a torque wrench type equipment with torque recording arrangement was set up on a lathe. The general set up of the equipment is shown

in Figure 2. A close up view of the recording arrangement with recorder chart mounted on a wooden disk on the chuck is shown in Figure 3.

Figures 4, 5 and 6 show the front view, side view and enlarged view of the differential mechanism of the torque recording device. One end of the sample was fixed by three 120° jaws on the 3-jaw universal chuck while the other end was fixed by two jaw block and the tail stock. Two arms were welded to one half of the tail stock jaw. One of these arms was stopped at a distance of two feet away from the specimen by an A-frame mounted on the compound tool holder of the lathe as shown in Figure 3. The other arm was left free. When the torque was applied by a rod inserted in the chuck and rotated by hand to cold work the specimen, the stopped arm was bent. The free arm remained straight. The difference between the two arms reflected the amount of torque applied and it was transmitted by a contact on free arm through a fulcrum on the fixed arm to the recorder chart. A pencil fixed on recording arm traced on the chart as the sample was twisted. The tracing on the chart thus recorded both the torque and the angle of rotation simultaneously.

The chart was calibrated by holding the spring balance horizontal on stopped arm at two feet away from the sample. The torque was applied by rotating the chuck by a rod inserted in the chuck and the reading of the spring balance multiplied by 2 ft length of the stopped arm lever gave the torque in ft lbs. A point for this torque was marked and similarly various points were marked in both clockwise and counterclockwise directions for torque up to 60 ft lbs.

Fig. 2. General set up of the equipment

Fig. 3. A close-up view of the recording arrangement

Fig. 4. Front view of the recording arrangement

Fig. 5. Side view of the recording arrangement

Fig. 6. Enlarged view of the differential mechanism of the recording arrangement

Material

The material used was 18-8 stainless steel five sixteenth inch hexagonal rod. As mentioned earlier, 18-8 stainless steel is a general term adopted in this country for alloys of chromium-nickel class, containing generally 17-20 percent chromium, 7-10 percent nickel as principal alloying elements, with sometimes certain additional alloying elements such as Mn, Mo, Si, etc., in small quantities. The chemical analysis was carried out by chemists in the State Highway Laboratory. The result of the analysis is shown in Table 1.

Table 1. Chemical analysis of 18-8 stainless steel sample.

Element	Percentage
Chromium	16.81
Nickel	9.17
Silicon	0.43
Manganese	1.05
Carbon	Negligible amount

The five-sixteenth inch hexagonal rod was cut into two and one-half inch lengths. The middle portion of one inch length was machined to a 5/16 inch cylinder, while both ends, three quarter of an inch, were kept as received. One end was center drilled for tail stock taper.

The samples were in annealed state and in unstabilized condition. This was tested by Strauss test to determine whether the sample was chemically stabilized by alloying with titanium or columbium.

For this test the specimen was sensitised at 1500° F for five minutes and quenched. It was then boiled in a flask containing 47 ml of concentrated

H_2SO_4 and 13 gms of $CuSO_4 \cdot 5H_2O$ per liter of the solution for 72 hours. After the test the specimen was found corroded by intergranular corrosion. This indicated that the sample was not chemically stabilized.

PROCEDURE

The equipment was mounted on the lathe for use as work table only as no electrical power was used. The chuck was rotated by hand with a rod inserted in the chuck. Since the tail-stock end of the sample was fixed the torque was transmitted to the specimen and by means of the differential torque recording arrangement shown in Figures 3, 4, 5 and 6 was recorded on the chart mounted on the wooden disc which is fixed to the chuck.

In order to measure the relative amount of phase transformation, Sanburn Twin Viso Recorder Strain Gage Amplifier as shown in Figure 7 was used. For this purpose one channel was utilised. Two similar inductance coils were connected through four terminals of the channel as two arms of an impedance bridge.

After specific degree of rotation the sample was removed for measuring the change in magnetic permeability, which is proportional to the amount of phase transformation. The cold worked sample was placed in the center of one of the inductance coils and the reading was observed. The sample was replaced by a number of chemically pure iron wires to get the same reading. The number of wires required was recorded after each application of cold work till the sample sheared off.

As the change in magnetic permeability is due to the formation of alpha-phase in cold worked stainless steel, increase in magnetic permeability

Fig. 7. A view of Sanburn Twin Viso Recorder with modification for measuring amount of magnetic transformation

can be used as a measure of the degree of α transformation and in the present case is related to the number of pure analytical iron wires needed to match the increased permeability of the cold worked specimen.

From the chart, the input work was calculated and the graphs of input work against the corresponding phase transformation that had occurred were plotted. As the analytical pure iron wire was 100% ferritic (alpha iron), the number of these wires gave relative amount of alpha iron produced during the cold work.

The sheared samples were then sectioned at a distance of a quarter of an inch away from the sheared end. Then they were mounted in bakelite plastic and polished to take diamond pyramid hardness numbers (DPH Nos.) across the diameter.

Since plastic deformation promotes both strain hardening and conversion of gamma iron to magnetic alpha iron, the hardness readings across the diameter were taken to get an indication of the degree of cold work from the center to the outside of the sample. These readings also gave a preliminary indication of magnetic strength along the cross section.

An iron-constantan compound thermocouple was connected through a potentiometer to measure subzero temperature. One juncture end of the compound thermocouple was kept in contact with the sample covered by dry ice through a teflon foamed plastic thermal shield. Another juncture end was kept at 0° C by immersion in a beaker containing crushed ice and water. Figures 8 and 9 show the arrangement for cold working the sample at subzero temperature and the arrangement for measuring subzero temperature.

The temperature measurement was calibrated by taking millivoltmeter readings at two points (fixed reference temperatures). One of these points

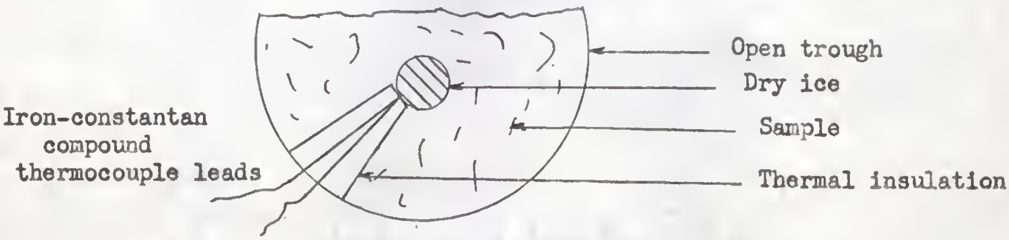


Fig. 8. Arrangement for cold working at subzero temperature

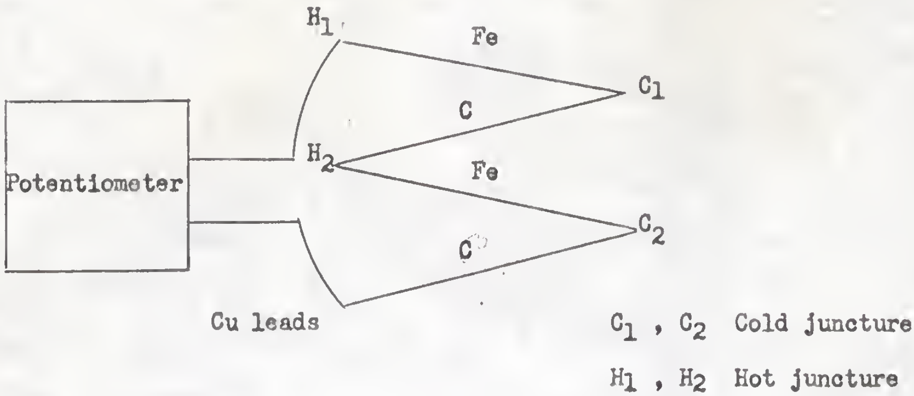


Fig. 9. Arrangement for measuring subzero temperature

was dry ice at equilibrium in acetone. This one juncture end of thermocouple was kept in a beaker containing crushed dry ice in acetone. While another juncture end was kept at 0° C by placing in crushed ice and water in a beaker. For another fixed point the freezing point of mercury was used. One juncture end was kept at 0° C by placing it in crushed ice and water while another juncture end was placed in acetone with mercury. Dry ice in small quantity was added to beaker containing acetone and mercury till mercury started freezing. At this point the millivoltmeter reading was taken. From these two points a calibration curve was drawn as shown in Plate I.

The compound thermocouple consisted of two wires of iron and two wires of constantan, joined alternately and fused at the joints. This was done to get magnified millivoltmeter readings so as to avoid errors in measuring temperatures.

RESULTS AND CONCLUSION

The 18-8 stainless steel samples were found to transform from face centered cubic austenite (gamma iron) to body centered cubic ferrite (alpha iron) by cold work. Table 2 summarises the relative increase in alpha iron corresponding to increased amount of cold work input in the eight samples. Four of them were cold worked at room temperature while other four were cold worked at subzero temperature. The table also gives the estimation of phase transformation by the number of analytical pure iron wires, [illegible] percentage transformation and the way in which the samples were tested.

Tables 3 and 4 give the relative increase in phase transformation corresponding to increased amount of cold work input at room temperature

EXPLANATION OF PLATE I

Calibration of iron-constantan compound thermocouple

A - Dry ice saturation point in acetone (-78.5° C)

B - Freezing point of mercury (-38.87° C)

PLATE I

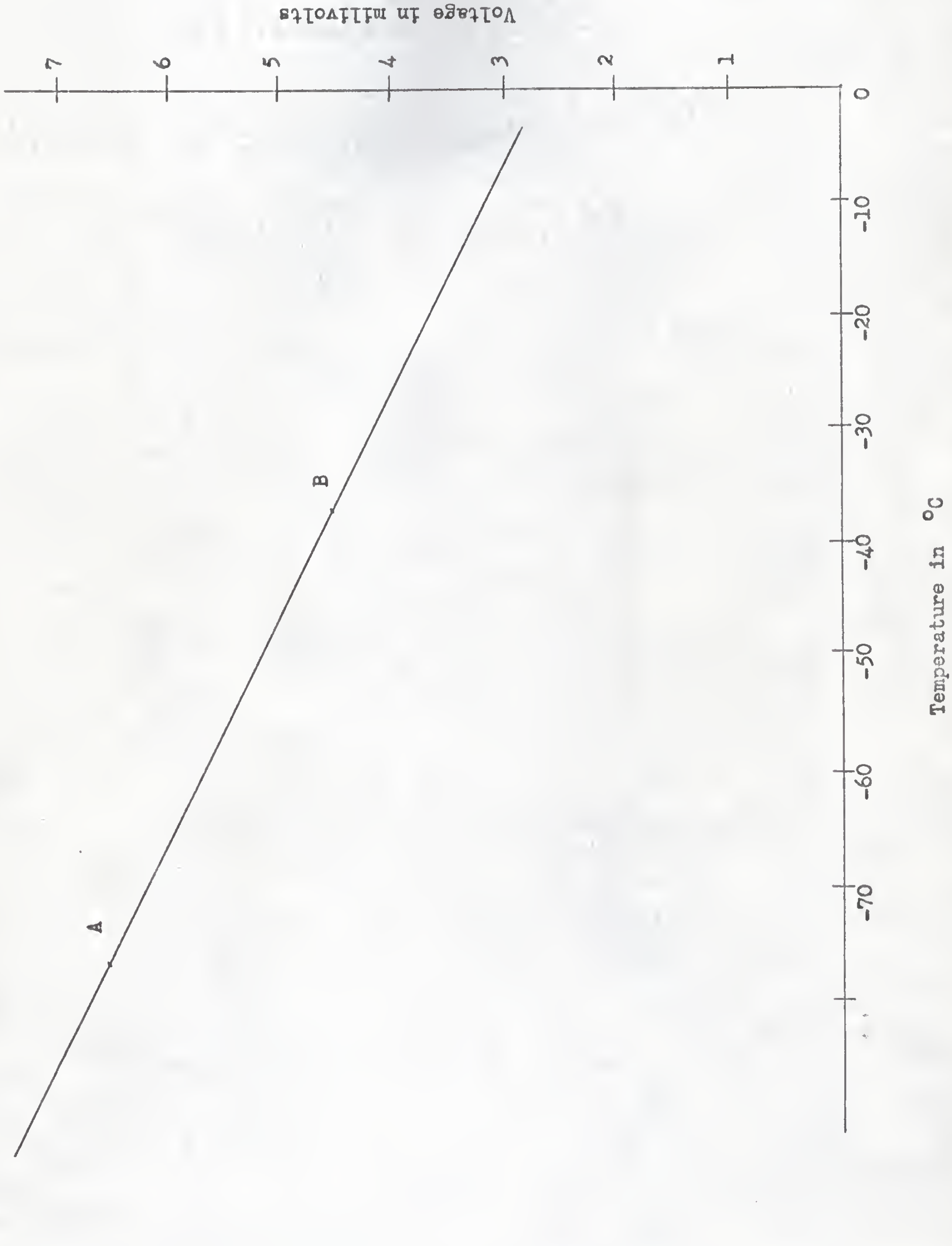

Voltage in millivolts
1
2
3
4
5
6
7
0
-10
-20
-30
-40
-50
-60
-70
Temperature in °C
A
B

Table 2. Summary of the results.

Sample number	Direction of rotation	Temperature	Cold work input	No. of wires corresponding to alpha phase	Percentage transformed
1	90° Both ways	Room (23.9° C)	6048 ft lb	65	5.58
2	"	"	5653 ft lb	53	4.55
3	"	"	5200 ft lb	31	2.66
4	360° Both ways	"	917 ft lb	21	1.8
5	"	-31° C	872 ft lb	108	9.27
6	"	"	960 ft lb	96	8.25
7	"	"	629 ft lb	61	5.24
8	"	"	1207 ft lb	164	14.1

and at -29.5° C respectively. Graphs were plotted from these readings and are shown in Plate II and Plate III.

From the data obtained it was observed that generally speaking phase transformation increases with increasing work input. At subzero temperature (-29.5° C), substantial amount of phase transformation was noted. This was expected in view of the fact that many authors who had studied this interesting phenomenon have reported that phase transformation produced by a given amount of cold work is greater as the temperature is lowered.

As indicated earlier in review of the literature all the authors, who have related the amount of phase transformation by cold work and magnetic permeability, used percentage reduction or percentage elongation for relating extent of cold work with degree of phase transformation. In this project, however, the phase transformation is related with amount of cold work input

Table 3. Increase in phase transformation with respect to increase in work input at room temperature.

Sample No. 1

Work input in ft lbs	250	750	1250	1802	2354	2856	3484	4112	4810	5520	6048
Number of wires	1	4	8	14	18	26	31	38	43	52	65

Sample No. 2

Work input in ft lbs	250	750	1250	1802	2354	2955	3556	4208	4860	5564	5652
Number of wires	1	2	4	8	13	19	24	27	34	46	53

Sample No. 3

Work input in ft lbs	528	1056	1584	2161	2738	3315	3943	4571	5200
Number of wires	1	2	4	8	10	15	19	23	31

Sample No. 4

Work input in ft lbs	164	340	528	716	917
Number of wires	2	5	8	15	21

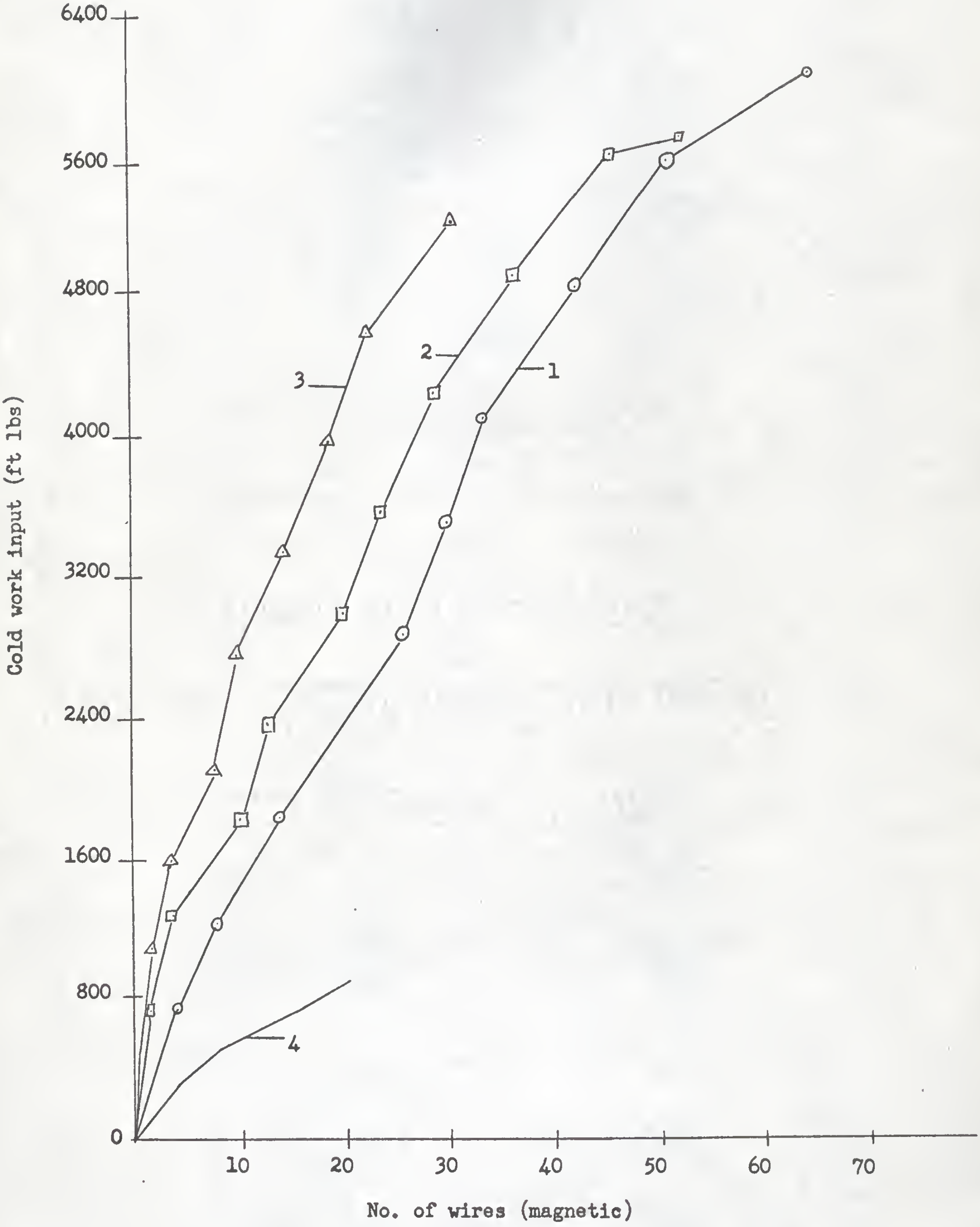
Table 4. Increase in phase transformation with respect to increase of work input at -29.5° C.

			Sample No. 5			
Work input in ft lbs	188	376	577	778	872	
Number of wires	11	29	55	100	108	
			Sample No. 6			
Work input in ft lbs	182	370	558	759	960	
Number of wires	12	28	43	76	96	
			Sample No. 7			
Work input in ft lbs	201	415	629			
Number of wires	13	37	61			
			Sample No. 8			
Work input in ft lbs	188	376	578	779	993	1207
Number of wires	12	32	59	104	140	164

EXPLANATION OF PLATE II

Relation between amount of alpha iron formed and cold work input at room temperature.

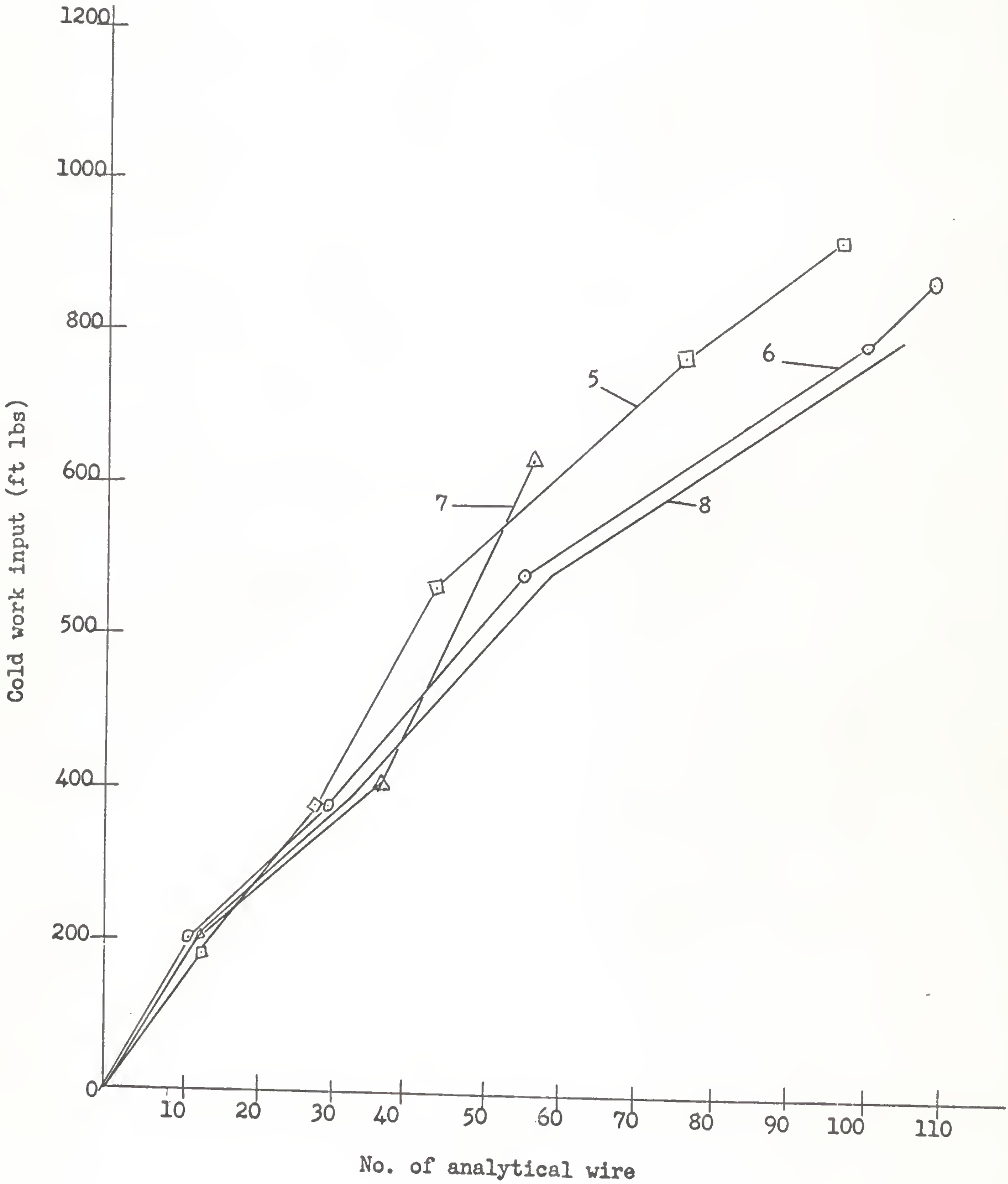
PLATE II


6400
5600
4800
4000
3200
2400
1600
800
0
Cold work input (ft lbs)
3
2
1
4
10
20
30
40
50
60
70
No. of wires (magnetic)

EXPLANATION OF PLATE III

Relation between amount of alpha iron formed and cold work input at -29.5° C.

PLATE III



1200
1000
800
600
500
400
200
0
Cold work input (ft lbs)
5
6
7
8
10
20
30
40
50
60
70
80
90
100
110
No. of analytical wire

in ft lbs. The percentage of phase transformation was obtained by comparing the equivalent area of the alpha phase in the specimen to the total area of the sample.

To find the work input, T-θ diagram was plotted for each stage of cold working. Since torque (T) in ft lbs multiplied by angle of rotation (θ) in radians gives work in ft lbs the area under the curve of T-θ diagram gave the work input.

Percentage of phase transformation was obtained by the formula:

$$\text{Percentage of } \alpha \text{ phase} = \frac{\text{Cross section area of the pure analytical iron}}{\text{Cross section area of the specimen}} \times 100.$$

Since the cross sectional area of the pure analytical iron wires represent the area of alpha phase in the cold worked specimen assuming pure analytical iron wires as 100 percent ferritic (alpha-phase).

Although this tendency was confirmed by this investigation the amount of transformation was not the same for all the samples tested under similar conditions. At room temperature samples 1, 2 and 3 were cold worked by applying the torque alternately in clockwise and counterclockwise directions through 90° and sample 4 was cold worked by applying the torque alternately through 360°. Sample 1 showed 5.58 percent phase transformation while sample 4 showed least phase transformation (1.8%).

At subzero temperature samples 5, 6, 7 and 8 were plastically deformed by applying torque alternately through 360°. Sample 8 showed 14.1 percent phase transformation while sample 7 showed least phase transformation (5.24%).

From the data plotted in Plates II and III it is obvious that the amount of transformation per unit work input was much greater at subzero temperatures than it was at room temperature. The variation in phase transformation both at room temperature and subzero temperature might have been due to the difference in rate of deformation as was indicated by Mathieu (8). During cold working of the sample, some of the input work was transformed to heat. This was noticeable especially while cold working at room temperature, where the specimen became warm and it was felt so by touching with finger. If the rate of deformation were slow enough so as to dissipate the heat generated during deformation to atmosphere, it is probable that more cold working could have been possible resulting in greater amount of phase transformation. Even though the deformation was done on the mid one inch long section of the sample, the end, fixed by chuck, also twisted slightly in some cases giving difference in phase transformations. Though care was taken to cold work all the samples with similar rates of deformation, it appeared that due to hand operation (manual) uniform rate of deformation was not achieved.

As the cold working of the sample progressed, the shining polished surface gradually became dull and rough, turning to orange peel surface before shearing off. A picture of a sample just before shearing off is shown in Figure 10 which gives an idea of the pattern of shearing action. Although it appears completely sheared off it was not so as central portion was still intact.

The samples were observed to shear off with different degrees of phase transformation depending upon the angles through which the cold work was carried out. It was anticipated that twisting alternately through

Fig. 10. A view of sample just before shearing off.

a small angle induces greater phase transformation per unit of cold work input, but this was not confirmed fully by experimenting with different angles through which the samples were cold worked, although such a tendency was noted.

The hardness numbers (DPH No.) across the diameter, one quarter inch away from the sheared end were measured by Vickers Armstrong Hardness Tester. The values obtained were tabulated for all the samples in Table 5. The graphs of hardness against the distance at 1/32 inch intervals from the edge across the diameter for room temperature conditions and subzero temperature conditions are plotted in Plates IV and V. At the center the hardness is less for all the samples and it goes on increasing as the radius increases till at the greatest radius the hardness is maximum. As strain hardening and phase transformation are both the effects of cold work this graph gives relative permeability along the cross section of the samples. Near the periphery (extreme ends of the diameter) hardness numbers are large suggesting that magnetic strength is maximum on the periphery where plastic strain was maximum.

While calibrating the chart for torque recording, a maximum discrepancy of 2 out of 25 lbs were observed. This gives the results an accuracy of ± 8 percent.

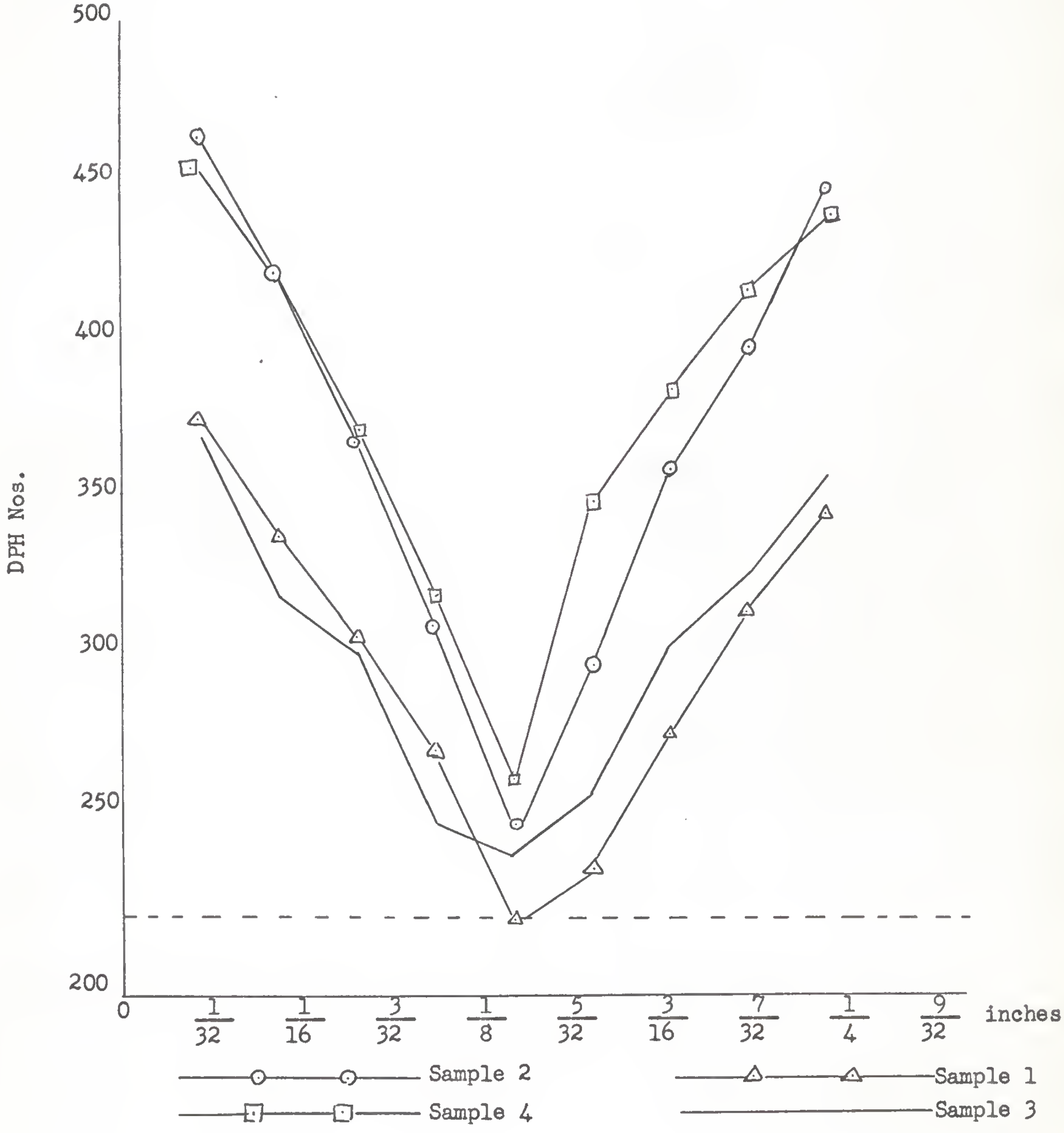
Table 5. Hardness across diameter in a section 1/4 inch away from sheared end.

Distance in inches across diameter from edge	DPH Nos. across diameter at 1/32 inch intervals							
	Sample No. 1	Sample No. 2	Sample No. 3	Sample No. 4	Sample No. 5	Sample No. 6	Sample No. 7	Sample No. 8
1/32	383	473	376	464	473	468	339	478
1/16	345	429	327	429	409	413	314	442
3/32	314	376	309	380	357	357	297	387
1/8	296	317	256	327	322	302	258	351
5/32	221	253	245	266	251	297	240	254
3/16	240	304	266	354	297	363	264	302
7/32	283	366	312	390	357	421	294	380
1/4	319	405	333	421	390	440	317	429
9/32	351	455	363	446	473	488	366	464

EXPLANATION OF PLATE IV

Hardness readings (DPH Nos.) across diameter at 1/32 inch intervals on samples cold worked at room temperature.

PLATE IV



500
450
400
350
300
250
200
DPH Nos.
0
1/32
1/16
3/32
1/8
5/32
3/16
7/32
1/4
9/32
inches
Sample 2
Sample 1
Sample 4
Sample 3

EXPLANATION OF PLATE V

Hardness readings (DPH Nos.) across diameter at 1/32 inch intervals on samples cold worked at subzero temperature.

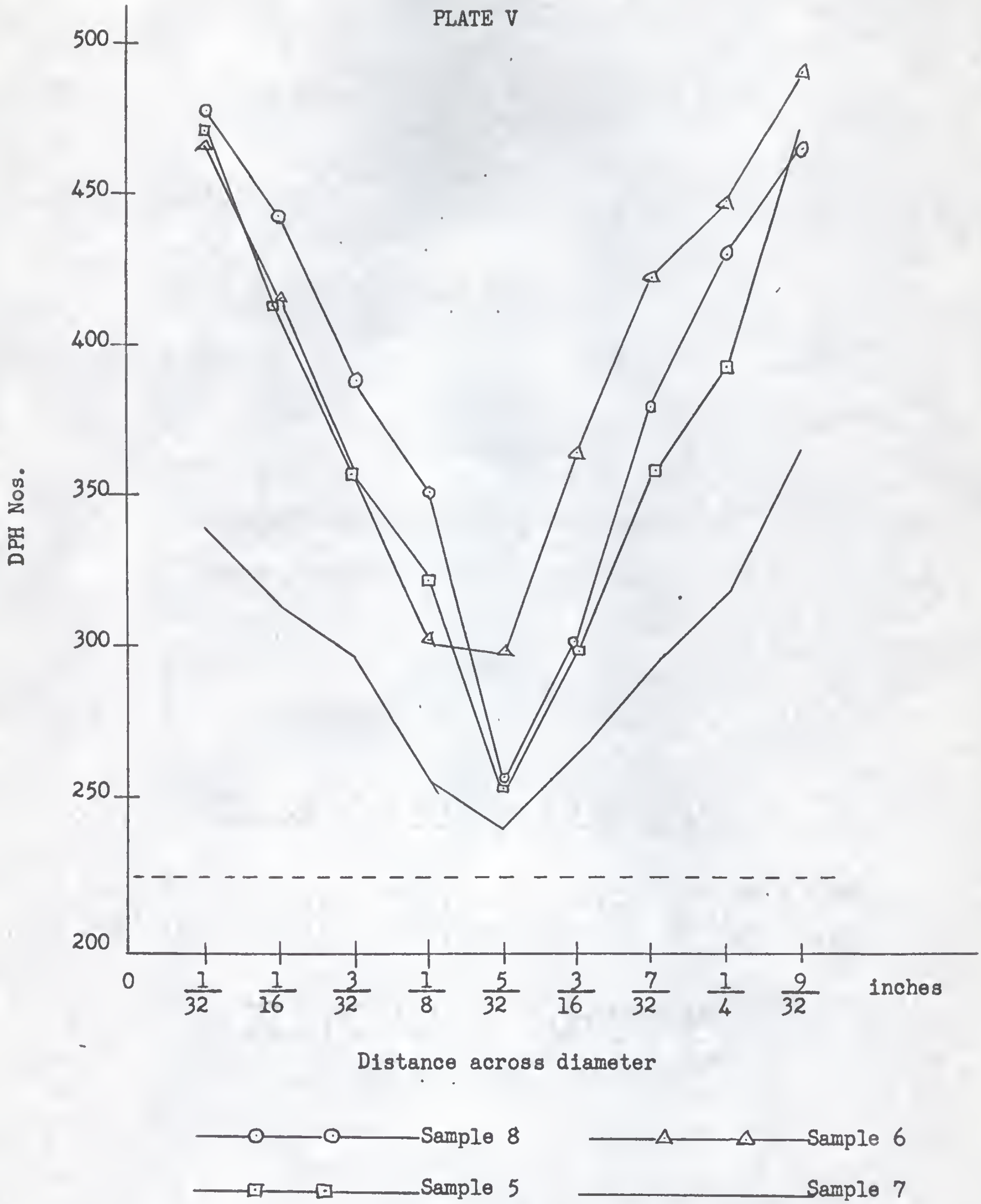


PLATE V
DPH Nos.
500
450
400
350
300
250
200
0
1/32
1/16
3/32
1/8
5/32
3/16
7/32
1/4
9/32
inches
Distance across diameter
Sample 8
Sample 6
Sample 5
Sample 7

DISCUSSION

Although no constant relationship between the cold work input and the degree of transformation was obtained with the type of equipment used, the author believes that with a more precise torque recording instrument and with a sophisticated temperature controlling device a more exact relationship could be obtained.

It was also noted that several cold worked samples at the sheared ends became permanently magnetic. This was not found in the literature cited. These permanently magnetised cold worked samples could lift several of the analytical pure iron wires from a short distance. This type of magnetic behavior is similar to one observed during machining or sawing or filing steel when the chips or filings of the steel gets permanently magnetised and sticks to the tool or file.

In the case of stainless steel this type of behavior may restrict the use of this steel where the retention of permanent magnetism may prove harmful.

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STUDY OF GAMMA-ALPHA PHASE TRANSFORMATION IN 18-8 STAINLESS STEEL BY COLD WORK

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AN ABSTRACT OF A MASTER'S THESIS

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When austenitic 18-8 stainless steel is plastically deformed (cold worked), the metastable face centered cubic phase (gamma iron) gradually converts to the stable body centered cubic phase (alpha iron). The purpose of this thesis was to obtain a quantitative relationship between the amount of cold work input and the resultant transformation.

Two and a half inches long 5/16 inch hexagonal 18-8 stainless steel rods were rounded off to 5/16 inch diameter along the mid one inch section. One end of the sample was clamped in the lathe chuck while the other end was fixed at the tail stock end. As the chuck was rotated by hand, a differential torque recording mechanism, mounted on the tail stock end of the sample provided a trace of the torque and the degrees of rotation on a calibrated chart. After specific degrees of rotation the sample was removed for measuring the change in magnetic permeability. The cold worked sample was placed in one coil of an inductance bridge and the reading was observed. The sample was then replaced by a number of one inch long 0.009 inch pure analytical iron wires required to give the same reading. The number of wires required was recorded after each application of cold work. This was repeated till the sample sheared off.

Samples 1 to 4 were cold worked at the room temperature while samples 5 to 8 were cold worked at -29.5° C. The cold work input was calculated from T-O diagram plotted for each stage of rotation. The percentage of phase transformation was obtained by comparing the cross-sectional area of the sample with that of pure analytical iron wires. The samples were then sectioned at a quarter inch from the sheared end and mounted in bakelite plastic for polishing to get diamond pyramid hardness numbers (DPH Nos.) across the diameter.

At subzero temperatures more transformation was observed per unit of cold work input. Higher hardness readings at the outside edge indicated a higher degree of transformation than at the center. A rough check of the magnetic strength at the center and the outside edge of the sample also showed greater magnetic strength on the outside edge.

Although transformation increased with increased cold work the ratio was not the same for all samples tested under identical temperature conditions. This might have been due to the difference in speed of deformation by hand. During cold working some of the mechanical energy was converted to heat energy and the sample was found to get warm. If the deformation speed were slow enough so as to dissipate this heat to the atmosphere, perhaps more transformation could have been obtained. A strange effect, not found in the literature cited, was observed about the retention of permanent magnetism at the sheared end of the sample.

Although no constant relationship between the cold work input and the degree of transformation was obtained with the type of equipment used, the author believes that with a more precise torque recording instrument and with a sophisticated temperature controlling device a more exact relationship could be obtained.